SEISMIC CHARACTERIZATION OF THE NOVEMBER 8, 10, AND 11, 1999 DEAD SEA UNDERWATER CHEMICAL CALIBRATION EXPLOSIONS USING CEPSTRAL MODELING AND INVERSION

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ABSTRACT

We have developed a cepstral simulation and inversion algorithm for analysis of regional seismic recordings of underwater explosions that determines the yield and depth of the explosions. The spectra of seismic recordings of the underwater blasts have strong time-independent spectral scalloping produced by the correlated bubble pulses and echoes of acoustic reflections from the water surface and in the water column. Signed cepstra, computed from the fourier transform of the log-amplitude spectra of regional seismic phases (Pn, Pg, Sn, and Lg), contain positive peaks produced by the bubble pulse correlation and negative peaks from the water-surface reflection. Theoretical cepstra of underwater explosions with assumed depths and yields are computed from simulated time sequences of bubble pressure pulses and water column reflections. The pulses are modeled as minimum-phase wavelets with the amplitudes of the bubble pulses set by the source physics of underwater explosions and the reverberation amplitudes

determined from the assumed reflection coefficients of the surface and bottom of the water column. A prototyped inversion algorithm, that determines explosion depth and yield, matches the synthetic model cepstra to data cepstra, stacked across all seismic phases and channels, by means of exhaustive search and downhill simplex and simulated annealing optimization methods. We have tested this algorithm on seismic recordings of three Defense Threat Reduction Agency's (DTRA) calibration chemical explosions detonated in the Dead Sea on November 8, 10, and 11, 1999. The three explosions all detonated at about 70 m and with yields of 500, 2000, and 5000 kg were recorded at the regional seismic stations EIL and MRNA on the high-frequency channels sampled at 40 Hz. This low bandwidth limits the resolution of short delay signals from water layer bounces but is adequate for resolving the bubble pulses from these events. The cepstral peaks were observed in all of recorded phases, and similar delay times were observed at two different stations for the largest explosion. The cepstral peak quefrencies (time delays) correspond to bubble pulse periods of 400, 550, and 800 ms. We estimate yields 650 ±140kg, 1950±750 kg, and 4200±500 kg for the 500, 2000, and 5000 kg explosions, respectively. Depth estimates of about 80 m from the combination of the bubble pulse period and interpreted surface reflections are not as well resolved, because of the shallow depths of the explosions and the limited bandwidth of the IMS data. However, the results are consistent with the known depths of 70 m. These results show that accuracy of this method is limited by the seismic bandwidth, particularly for small, shallow events. Overall, this study points out the importance of using seismic data for detection and characterization of underwater explosions in inland seas.

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OBJECTIVES

The problem of the identification of underwater blasts has gained increased interest recently in the context of the monitoring of the Comprehensive Nuclear Test-Ban Treaty (CTBT) which was opened for signature by the United Nations on 24 September 1996. Annex 1 to the Protocol of the CTBT calls for the installation of an International Monitoring System (IMS) including six hydroacoustic stations and five so-called "T-phase" stations. T-phase stations are seismic sensors located near the coast that can detect hydroacoustic phases converted to seismic phases at the coast. Thus, only 11 stations will be available specifically for monitoring underwater events. If an explosion occurs in the ocean, but near the coast outside of the SOFAR channel, long-range propagation of hydroacoustic signals may be blocked, and there is a possibility that the events may not be easily detected by the IMS assets directed toward the underwater explosions. Because of the relatively larger number of seismic stations, 170 primary plus auxiliary stations, called for the CTBT Protocol for the IMS, near-coast seismic stations may have a better chance of detecting and characterizing underwater events on the continental slopes, outside of the SOFAR channel, or in confined seas. Moreover, early-arriving seismic signals, such as *Pn*, *Pg*, *Sn*, and *Lg*, produced by mode conversion of acoustic waves in the water in the vicinity of the source, may carry more useful information about in-situ source conditions than later arriving T phases that may be affected by propagation path effects in the oceanic water column.

Baumgardt and Der (1998) showed numerous examples of underwater explosions recorded at seismic stations and how they can be best characterized by spectral and cepstral analysis. A simple model for underwater explosions was developed and synthetic cepstra were produced that reproduced most of the essential features of observed underwater explosion cepstra. The main features were bubble pulses, which produce positive cepstral peaks, and the first surface reflection that produces a strong negative cepstral peak. The timing and relative amplitudes of these cepstral peaks provide useful constraints on the depth and yield of underwater explosions.

The following are the objectives of this study:

- Collect appropriate seismic data from explosions and earthquakes in water-covered and nearby areas for study, preferably with corresponding hydroacoustic data that may be used to validate results of calculations.
- Gain an improved understanding of the effects of the water column on the seismic data, and use this understanding to determine parameters such as in the water column/not in the water column, water depth, and others.
- Develop an algorithm to extract information from seismic records of events in and near water-covered areas to aid in monitoring the CTBT.

RESEARCH ACCOMPLISHED

This paper describes the results of our development and application of a spectral and cepstral analysis algorithm described in earlier presentations (Baumgardt, 1999a, Baumgardt and Freeman, 2000) and an annual technical report (Baumgardt, 1999), designed to estimate yield and depth of underwater explosions. In the earlier studies, the results of analysis of presumed underwater explosions detonated in the Norwegian and Baltic Seas were discussed. Estimates of denotation depths and yields of the explosions were presented. However, we had no ground truth information with which to compare the results of our analyses. In November, 1999, under DTRA sponsorship, the Seismology Division of The Geophysical Institute of Israel detonated three chemical explosions in the Dead Sea at a depth of 70 m and with known yields of 500, 2000, and 5000 kg (Gitterman et al., 1999). These events were recorded by two seismic stations of the IMS, Meron (MRNI) and Eilat (EIL), and thus provided us with actual underwater explosions with ground truth which can be used to evaluate the algorithm. In this paper, we review the cepstral analysis and modeling approach, discuss the results of its application to the Dead Sea calibration events, and describe a new graphical user interface (GUI) prototyped in Matlab for the application of the algorithm.

THE DEAD SEA CALIBRATION EXPLOSIONS – NOVEMBER 8, 10, AND 11, 1999

The location and source parameters of the Dead Sea calibration explosions of November 8, 10, and 11, 1999 have been described in detail by Gitterman et al, 1999. Figure 1 shows a map of the location of the explosions and the propagation paths to the two IMS stations, MRNI and EIL.

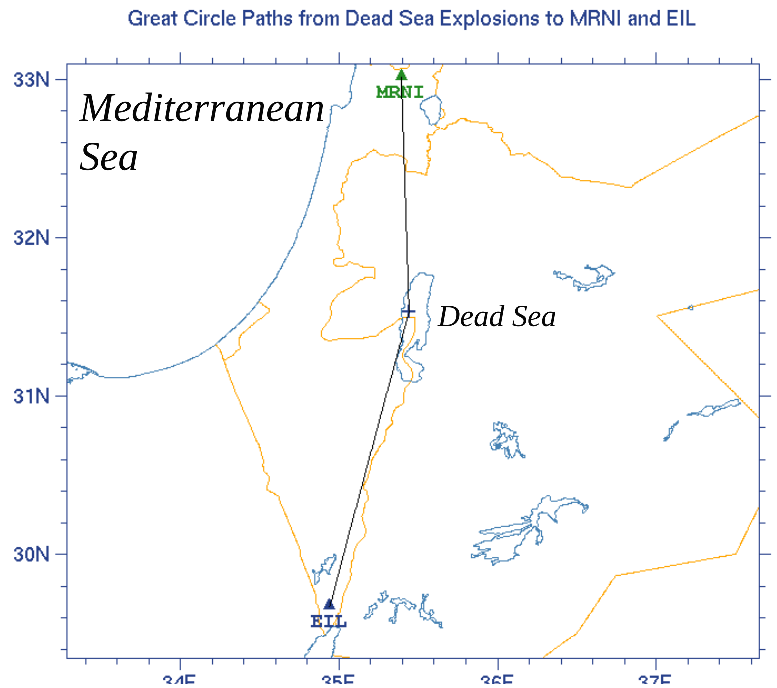


Figure 1: Plot of map of the IMS stations that recorded the calibration explosions in the Dead Sea.

Figures 2 and 3 below show the waveforms of the explosions recorded at EIL and MRNI, respectively, with the phases reported in the Reviewed Event Bulletin (REB) plotted on the waveforms.

<u>*It should be noted that the 500 kg event of November 8 was not recorded at EIL. It is notable that these three events had very different waveforms, which are evidently due to the differences in source parameters of the events.*</u>

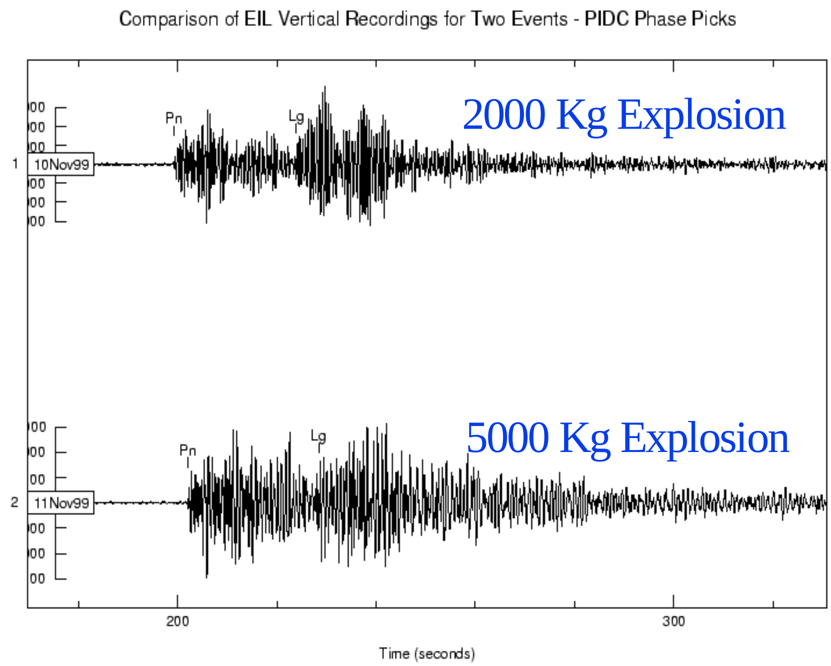


Figure 2: Waveforms of the November 10 and 11, 1999 Dead Sea explosions recorded at EIL.

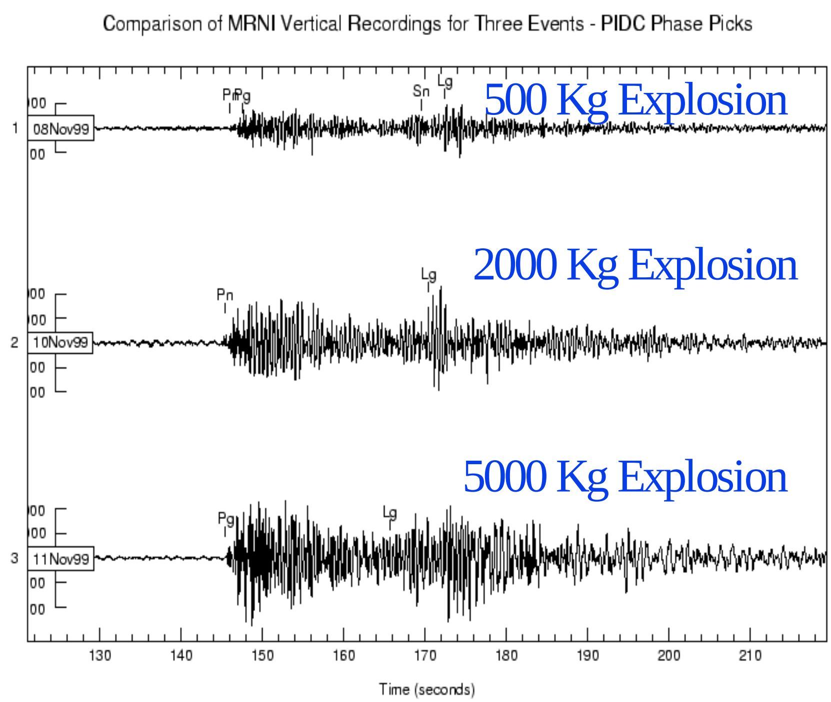


Figure 3: Plots of the MRNI recordings of the November 8, 10, and 11, 1999 Dead Sea Explosions.

CEPSTRAL ANALYSIS

Baumgardt and Zeigler (1988) and Baumgardt and Der (1999) describe the cepstral analysis technique in detail. In brief, the spectra of each of the phases identified in Figures 2 and 3 in a 25 second window are computed and corrected for instrument response and linear trend. A second Fourier transform is then taken of the log of the real part of the spectra, which gives what is called the "cosine" or "signed" cepstrum. The peaks which appear in these cepstra correspond in quefrency (independent variable of the cepstrum) which gives the time delay corresponding to the spectral modulations produced by the explosion bubble pulse and reflection from the free surface.

We have found that averaging, or "stacking", spectra or cepstra, across multiple channels enhances the spectral modulations and cepstral peaks caused by the source and reduces the effects of local site scattering and noise. In our earlier studies of underwater explosions off the coast of Scandinavia (Baumgardt, 1999a,b), we had array data available, and array averaged spectra and cepstra were much improved over those computed for single channel data. For three-component data, such as the IMS stations recordings of the Dead Sea events, array data was not available. However, we have found that stacking cepstra or spectra across the three-component channels (Z, NS, EW) provides more improved results over single channel data. Finally, spectra and cepstra can be stacked across multiple stations that record the event, such as MRNI and EIL for the Dead Sea events.

Stacked cepstra can be computed by either stacking the spectra, and computing the cepstra from the stacked spectra, or by computing cepstra for each channel and stacking the cepstra. We have found little difference in cepstra computed by either spectral or cepstral stacking.

Figures 4 shows the processed spectra and cepstra for the phases recorded at EIL from the 5000 kg explosion of November 11. In this case, the spectra have been stacked across the three components and the cepstra were computed from the stacked spectra.

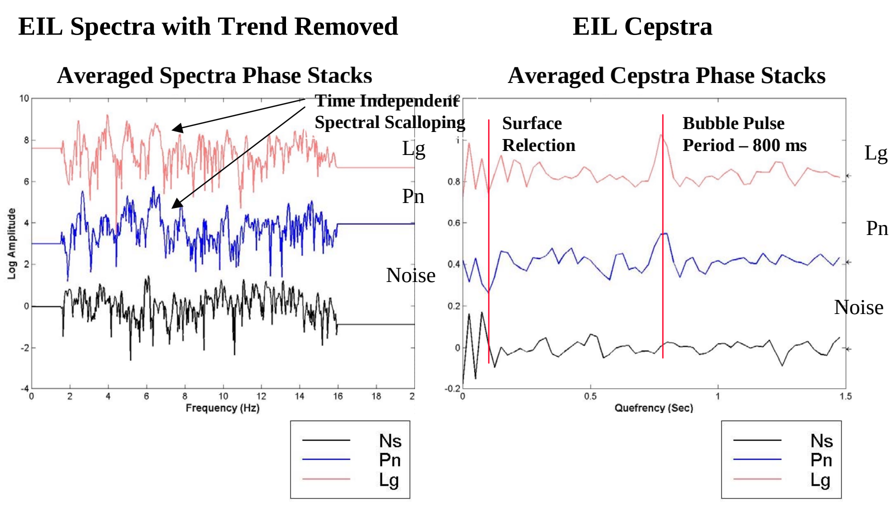


Figure 4: Spectra and cepstra for the EIL recordings of the November 11, 1999 5000 kg Dead Sea Explosion.

The spectra on the left have been processed by removing the instrument response and have been tapered to a flat level on the low and high frequency ends. The spectra are for each of the phases reported by the PIDC for this event (*Pn*, *Lg*) and the noise ahead of the *Pn (Ns)*. The spectra clearly show spectral modulations that appear in all phases but not in the noise, as indicated in the figure. These spectral modulations produce peaks in the cepstra of the two phases as shown on the right of Figure 4. Weak negative peaks at low

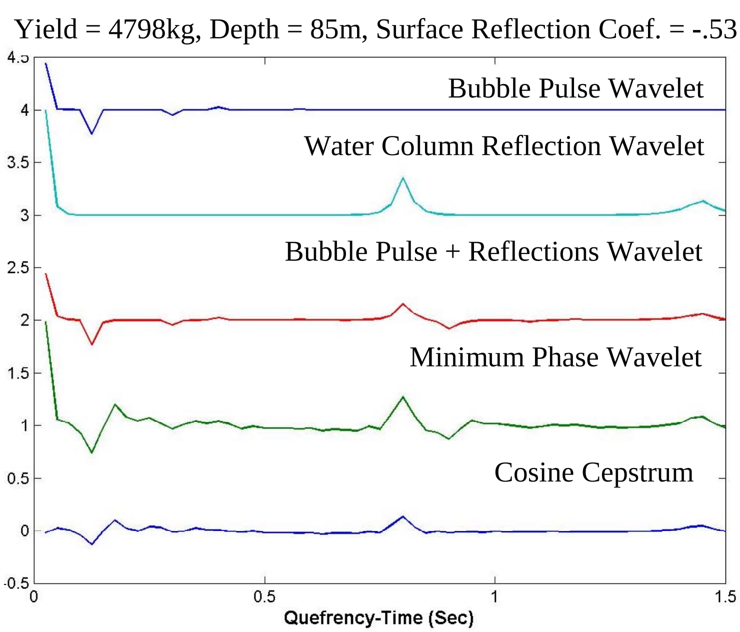
quefrency may correspond to reflections from the free surface and the very strong positive peaks are due to the bubble pulse. The estimated bubble pulse period for this event is about 800 ms.

CEPSTRAL MODELING AND INVERSION APPROACH

Spectra of underwater explosions contain very distinct spectral modulation or scalloping in all phases that does not appear in the noise. Spectra of this kind have been shown to be caused by source multiplicity, either due to ripple fire in mine blasts (Baumgardt and Ziegler, 1988) or by water column reverberations and bubble pulses in underwater explosions (Baumgardt and Der, 1998).

We have developed a modeling and inversion algorithm for the characterization of cepstra of underwater blasts which was described by Baumgardt (1999a,b). Because the cepstrum reflects the correlation structure of the source-produced pulses, it is easier to model than the waveforms themselves. The removal of the polynomial trend in the spectra also eliminates the spectral effects of the propagation path and thus, only the source correlation structure is retained in the cepstra. We showed in our earlier study (Baumgardt and Der, 1998) that modeling cepstra does not require information about the propagation path or receiver function, nor does it even require much information about the source time function. Thus, modeling cepstra requires many fewer parameters than modeling waveforms or spectra.

The modeling techniques described by Baumgardt and Der (1998) are used to interpret this event. The model construction is illustrated in Figure 5.



Modeling Method

- Compute Wavelets for Bubble Pulse
- Compute Wavelets for Water Column Reflection
- Convolve Source, Bubble Pulse Wavelet and Reflection Wavelet,
- Compute Cepstrum of this composite waveform to produce Cosine Cepstrum

Figure 5: Modeling approach for calculating synthetic cepstra.

We convolve wavelets for the bubble pulse, shown on top, and water column reverberation, shown as the second trace, for a given assumed yield and depth in the water. The theory for calculating bubble pulse wavelets was taken from the literature and is described by Baumgardt and Der (1998). Other parameters that must be specified include average water column depth, that can be obtained from the bathymetry, and the surface and water bottom reflection coefficients. As in the case of water depth, these parameters can be estimated with some degree of accuracy, but it is also conceivable that they can be inferred from the data.

We assume that the acoustic waves in the water reflect from first-order discontinuities at the bottom and the surface.

We then compute the cepstrum of this composite wavelet, which is shown at the bottom of Figure 5. We also show a minimum phase wavelet reconstruction from the cepstrum which is identical to the original wavelet. This shows that our modeling method assumes minimum phase wavelets.

Finally, we seek a synthetic cepstrum that matches the observed cepstrum. For this purpose, we compute the correlation coefficient between the stacked observed cepstrum and the synthetic cepstrum and seek a cepstrum that provides the highest correlation. We first have considered an exhaustive search method, where the parameter space of blast yield and depth is gridded and synthetic cepstra are computed for each grid point. Then, we correlate the synthetic cepstra at each grid point and compute a correlation coefficient surface over the depth/yield parameter space and look for the peaks in the depth/yield surface.

Figure 6 shows the resultant correlation coefficient surface plotted in contour (left) and as a 3-D surface rendering (right).

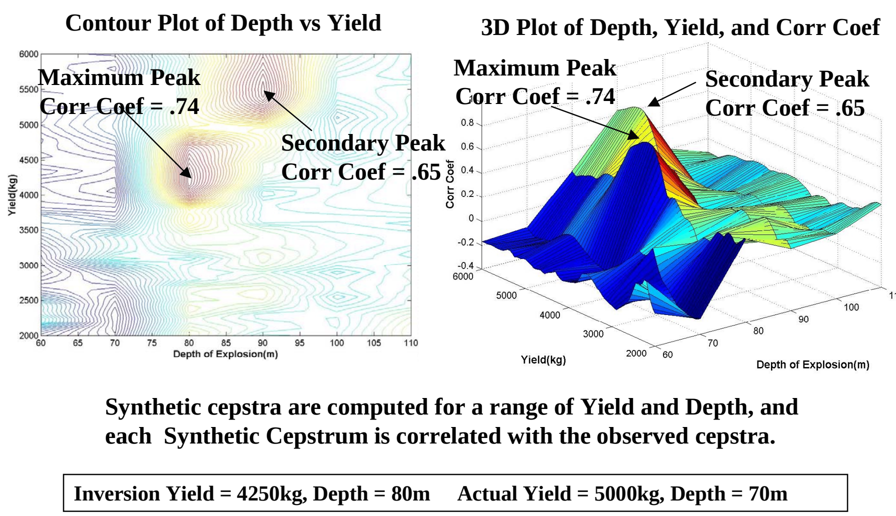
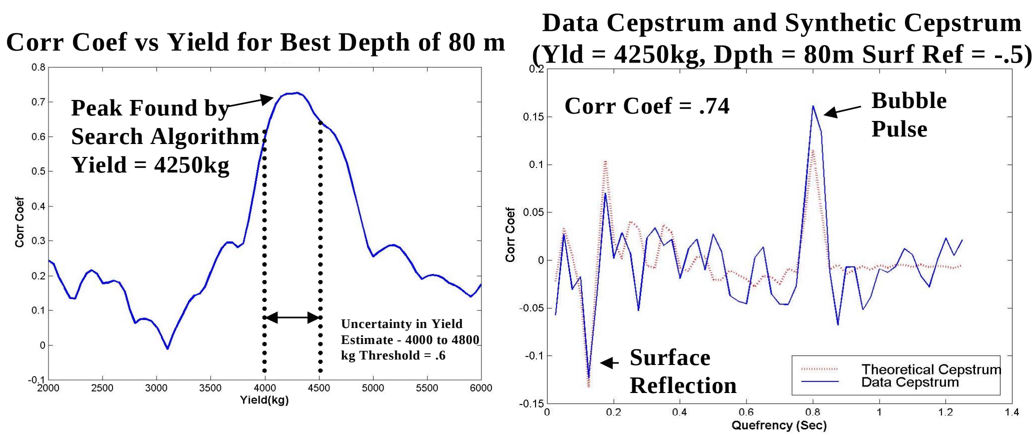


Figure 6: Contour plots (left) and 3 D plot (right) of the correlation surface between synthetic cepstra and observed cepstra for the EIL recording of the November 11, 1999 Dead Sea explosion.

Both displays have a distinct peak in the correlation, with a maximum correlation coefficient of 0.74, corresponding to a water depth of 80 m and yield of 4250 kg. The sensitivity to yield is illustrated in Figure 7, which shows the correlation coefficient as a function of yield for the depth of 80 m. The maximum peak was at 4250 kg, but the range covers the true value of 5000 kg. Figure 7 also shows a direct comparison of the observed stack cepstrum and the best-matching synthetic cepstrum. This comparison shows that, although the match is not perfect, reasonably good matches of the essential features, the negative peaks of the water column reflection and the bubble pulses, have been attained.

In addition to the correlation coefficient, we have also used the L1 and L2 norms, described in detail by Baumgardt (1999b). Also, we have experimented with optimal search algorithms for inversion, including the downhill simplex optimal search and simulated annealing methods, along with the exhaustive search method described above, to find the best fitting synthetic cepstrum. Details about optimal search algorithms can be found in Baumgardt (1999b).



Cross section of correlation surface at water depth showing apparent yield resolution.

Comparison of synthetic cepstrum with highest correlation (.74) with Stack EIL data cepstrum

Inversion Yield = 4250kg, Depth = 80m   Actual Yield = 5000kg, Depth = 70m

Figure 7: Cross section of the correlation peak (left) and comparison plot of the best matching synthetic and observed cepstra (right).

MATLAB GRAPHICAL USER INTERFACE

We have developed a Graphical User Interface (GUI) to facilitate the user's ease in interfacing with the cepstral simulation and inversion algorithm described above. The GUI for the Cepstral Modeling and Inversion Tool is Windows based, and was designed using Matlab, and can run on either a PC or UNIX workstation. The input data include the standard IDC database flat files (.origin, .arrival, .assoc, .w). The main GUI windows are described below.

The Stations and Channels GUI window (Figure) allows the user to choose the waveform (.w) file to process, and the prefix for the database files associated with the waveform. All of the corresponding stations and channels for the waveform file are displayed, and the user chooses the stations and channels to process. The Save Selection push button saves the parameters chosen for processing the data cepstrum, and the Close push button closes the Stations and Channels GUI window.

The user may compute a data cepstra, using the parameters set in the Stations and Channels GUI window. The parameters for the data cesptra are set in the Process Data GUI window (Figure 9a). The .w file being used is displayed, as well as the inprefix for the database files. The window used (Hanning, Parzen, or Kaiser), window length, and frequency range may be set. The options for noise subtraction, instrument response removal in processing the data cepstra, as well as individual plotting of the stack spectra for each station are available. Also, the polynomial fit degree may be set. The user has the choice of using either a Stacked Spectrum or Stacked Cepstrum method for computing the data cepstra, and the length of the data cepstra may be changed. The user also chooses the directory location for the cepstra files to be saved. When all of the input parameters are set, the user presses the Process Cepstrum button; plots of the data cepstra are displayed, and the cepstra data and necessary variables for the inversion algorithm are saved to the chosen directory. The Close pushbutton closes the Process Cepstrum GUI window.

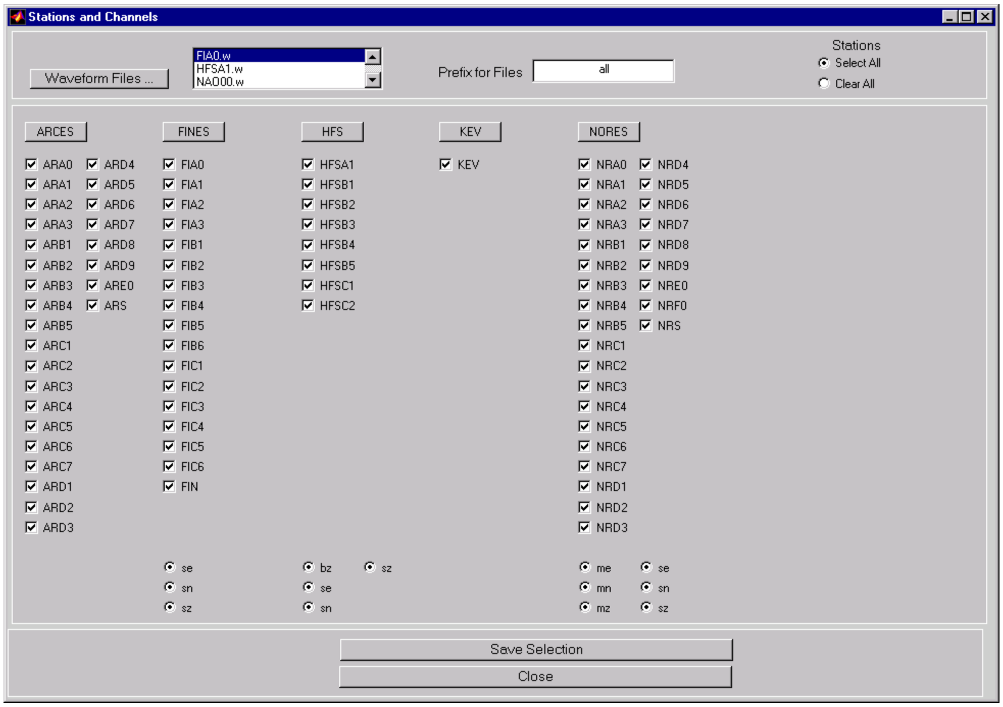
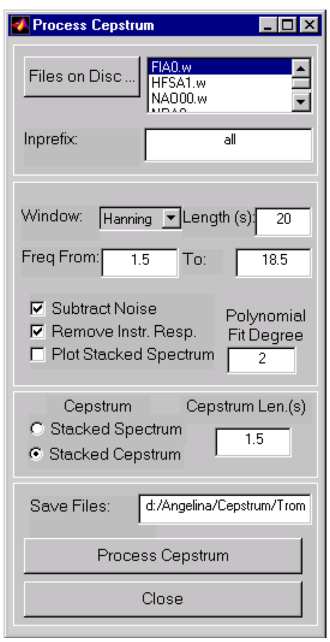
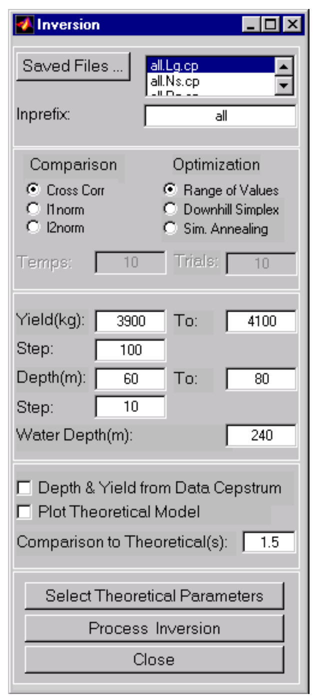


Figure 8: Stations and Channels GUI



(a)



(b)

Figure 91: Process Data Cepstrum GUI Window (a) and Inversion GUI Window (b)

The parameters for the inversion of the data cepstrum with the model cepstra are set in the Inversion GUI window (Figure 9b). The saved data cepstra files in the current directory are displayed. However, other data files may be selected. The inprefix may also be edited. A Comparison method for the inversion, either Cross Correlation, L1 Norm, or L2 Norm can be selected by the user. The Optimization method, either Range of Values, Downhill Simplex, or Simulated Annealing is also selected. Choosing the Simulated Annealing method causes the Temperatures and also the Trials edit boxes to become active for the user to edit. If the user selects Range of Values as the Optimization method, the range of yields of the explosion, as well as the steps in yield values are displayed, and may be edited. The same is true for the depths of the explosion. If Downhill Simplex or Simulated Annealing are chosen for the Optimization method, only one edit box for depth, and one edit box for yield is displayed; the user utilizes these to specify the starting values for the Optimizations. It is likewise possible to set the Water Depth at the explosion location.

Checking the Depth and Yield from Data Cepstrum checkbox displays the data cepstrum at the beginning of the inversion process. The user, by clicking on the surface reflection and first bubble pulse, gives the algorithm information for determining a good starting point for depth and yield. This option for initializing depth and yield may be used with all of the optimization methods available. If the Plot Theoretical Model is selected, a figure containing the theoretical cepstrum and its components is displayed during the inversion process. The Select Theoretical Parameters pushbutton opens a GUI window for the theoretical parameters used for cepstral modeling. In this window the surface reflection, bottom reflection, decay constant for bubble pulse, takeoff angle in degrees, number of bubble pulses, and bubble pulse weighting may be edited. The Process Inversion pushbutton runs the inversion with the set parameters. Plots of the data cepstra and of the optimization method are displayed, as is a comparison between the data cepstrum and the best theoretical cepstrum match found by the chosen optimization method.

SUMMARY AND CONCLUSIONS

The results of our analysis of the three Dead Sea events, using the L1 norm fit parameter, are summarized below:

Bubble Pulse Periods were resolved for all three explosions
- –November 08, 1999: Bubble Pulse Period = 400 ms
- –November 10, 1999: Bubble Pulse Period = 550 ms
- –November 11, 1999: Bubble Pulse Periods = 800 ms

Exhaustive Search Cepstral Inversion Results Using L1 Norm
- –November 08, 1999 Actual Yield = 500 kg, Depth = 70 m
  - Estimated Yield = 650 kg ± 140 kg (Threshold = .948) at Depth = 80 m
- –November 10, 1999 Actual Yield = 2000 kg, Depth = 70 m
  - Estimated Yield = 1950 kg ± 700 kg (Threshold = .955) at Depth = 80 m
- –November 11, 1999 Actual Yield = 5000 kg, Depth = 70 m
  - Estimated Yield = 4200 kg ± 500 kg (Threshold = .975) at Depth = 80 m

The accuracy of the yield estimates is controlled by the available bandwidth of the data. Large events provide the most accurate estimates since the longer delay times of the bubble pulses require less bandwidth than smaller events. Also, deeper events are resolved more accurately than shallow events for the same reasons – less bandwith is required to resolve the longer delay times of deep events than those of shallow events.

The results of this study indicate that the cepstral analysis and inversion algorithm provides a method for inferring source parameter of underwater explosions using seismic data. As discussed earlier, underwater explosions in regions like the Dead Sea, where acoustic signals do not get into the SOFAR channel of the open ocean, will not be detected by hydroacoustic sensors of the IMS. Thus, it is important that methods like the one described in this paper should be developed for application to seismic data as well as for hydroacoutic data.

<u>Key Words</u>: underwater explosions, yield estimation, discrimination, spectrum, cepstrum, modeling, inversion

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